Utilization of waste heat for pre-heating of anodes

Martin Grimstad, Kim Ronny Elstad, Asbjørn Solheim, Kristian Etienne Einarsrud

Abstract Carbon anodes are replaced on a regular basis in Hall-Héroult cells as they are consumed by electrochemical reactions. Upon insertion of new anodes, bath will freeze locally as a result of low bath superheat and comparatively low anode temperature, creating an insulating layer on the anode surface, thereby delaying further production. In the current work the potential for pre-heating anodes directly utilizing waste heat from off-gas and spent anode butts is investigated using a numerical model realized in COMSOL and industrial measurements at the Alcoa Mosjøen smelter. Anode core temperatures over 150 °C and surface temperatures over 250 °C were found when using butts as a direct heat source. Frozen bath samples from both pre-heated and regular anodes were collected and analysed using computer tomography (CT) in order to assess how various heating strategies influences frozen bath morphology.

Key words: Anode pre-heating · Waste heat · Energy efficiency

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1 Introduction

The heat balance for the Hall-Héroult cell is a major concern in the process [1]. As a result of increasing energy costs and greater environmental awareness, modern cells are now built to preserve more of the heat produced in the process, allowing for further reduction of the specific energy consumption. Due to the continuous consumption of carbon following the electrochemical reaction occurring in the cell, the anodes are replaced after 25-30 days, depending upon the current density and anode size. With 20-40 anodes in a typical cell, an anode replacement is thus performed every 1 to 3 days [1]. When an anode is placed in the molten bath, the temperature of the anode is between 15 and 30 °C, while the bath will be close to its liquidus, i.e. 940-970 °C [1]. Due to this temperature difference, a layer of frozen bath will form underneath the new anode, which, depending upon process conditions will melt within some hours after insertion [2, 3]. The thermal imbalance and frozen bath layer introduces a latency in production, affects the bath density [2] and disturbs the MHD stability of the cell [4].

The thermal issues related to anode change can be mitigated by pre-heating the anodes prior to insertion. Fortini et al. [5] heated anodes to surface temperatures of about 500 °C using 30 kW heaters and found an increase in current efficiency of 0.5-1 % over 60 days. Correspondingly, Jassim et al. [6] found that preheating anodes up to 300 °C resulted in a 42% faster evolution in current during the initial 6 hours of operation - in theory improving cell stability and current efficiency, as well as improving the local heat deficit. As pointed out by Jassim et al. [6], however, benefits arising from anode pre-heating should not be negated by increased energy consumption - i.e. the usage of waste heat should be considered.

There are numerous heat sources at an aluminium plant that could be utilised for heat recovery, as discussed by Nowicki and Gosselin [7], demonstrating that for instance off gas from the anode baking furnace can contain several MWh per year with temperatures reaching up to 300°C. Although a considerable heat source - the transport of hot anodes from the baking furnace to the potline will necessarily result in some heat loss as well as logistics related issues. Considering heat sources within the potline, the off gass from the cell is believed to have temperatures of about 100°C [7], while surfaces within the cell itself could have considerably higher temperatures.

Another source of heat from the electrolysis cell are spent anode butts, which upon removal will have temperatures of up to 900°C with approximately 1/4 of their initial weight - corresponding to approximately 70 kWh of heat per anode. Normally, butts are cooled down without heat recovery before they are cleaned and reclaimed. Considering the number of anodes replaced in a potline per day, butts can represent a substantial heat source.

In order to quantify the potential for pre-heating using off-gas and anode butts, simple 2D simulations were performed utilizing COMSOL Multiphysics® [8]. Preheating with butts has been tested on industrial scale at the Alcoa Mosjøen smelter, aiming to describe thermal and electrical performance after different times of heating. Furthermore, bath samples were collected from both pre-heated and normal anodes in order to assess the influence of pre-heating upon the local heat deficit.

2 Simulations

In order to assess the potential for anode pre-heating, a series of parametric studies were performed using COMSOL Multiphysics® [8]. A schematic of the two concepts considered with principal parameters is shown in figure 1. All simulations were realized using 2D components, using the Conjugate Heat Transfer and Turbulent Flow Modules (k-ω turbulence model), along with the option for weakly compressible flow. Surface-to-surface radiation was enabled for both concepts. When pre-heating using butts 1a, all anode surfaces were chosen as diffusive surfaces with $\varepsilon = 0.93$. When heating within the superstructue 1b, the anode, crust and stubs were chosen as diffusive surfaces with $\varepsilon = 0.93$. The ambient temperature was set to 20°. All simulations were performed in transient mode with the *fine* mesh option, corresponding to a resolution of 0.24 mm around the anode surface. The stubs in the simulations were given the parameters for high-strength alloy steel, while the fluid was assumed to be air, cf. [8] for corresponding values. Anodes were assumed to have a constant density of 1600 kg/m^3 and heat capacities based on data provided by JANAF [9]. Simulations were run with initial conditions corresponding to the fluid initially being at rest, with initial temperatures shown in figure 1.

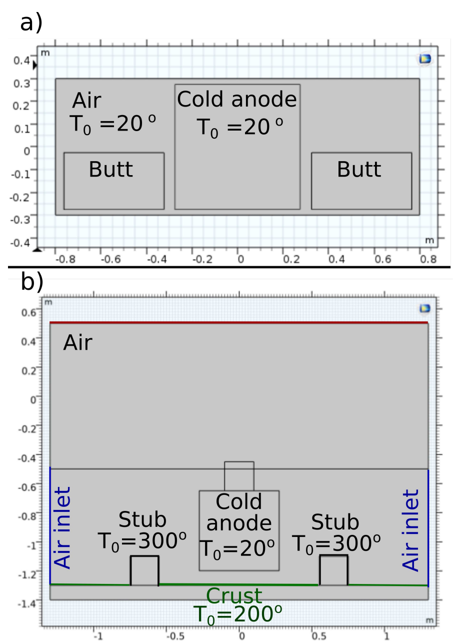

Fig. 1 Schematic of concept for anode pre-heating utilizing butts (a) and off-gas within the superstructure (b) along with initial conditions for temperature. The outer boundary conditions for (a) were set to adiabatic or convective in two separate cases in order to estimate the effect of insulation, while the boundary conditions for (b) were as specified.

2.1 Pre-heating using butts

Four different scenarios are considered, summarized in table 1, representing initial temperatures of the butts, T_{butt} of 900 and 700°C and adiabatic as well as convective boundary conditions on the outer boundary of the domain, cf. figure 1a. The convective boundary condition was represented by a constant heat transfer coefficient of 2 W/mK and ambient temperature of 25°C. The temperature in the anode center, T_{core}, centerpoints of top (T_{min}) and bottom (T_{bottom}) surfaces as well as the maximum temperature on the side wall (T_{max}) after 210 minutes is given table 1. Sampling points and the temperature distribution for Case 1a is shown in figure 2a for reference.

Table 1 Principal results and conditions for cases considered. Temperature values correspond to 210 minutes pre-heating.

Pre-heating with butts							Pre-heating in cell							
Case	T_{butt} (°C)	Boundary cond.	T_{core} (°C)	T_{bottom} (°C)	T_{max} (°C)	T_{min} (°C)	Case	T_g (°C)	u_g (m/s)	h (cm)	T_{core} (°C)	T_{bottom} (°C)	T_{max} (°C)	T_{min} (°C)
1a	700	Adiabatic	109	103	150	85	2a	180	0.5	10	77	128	154	47
1b	700	Convective	106	100	142	82	2b	180	0.5	40	73	132	140	44
1c	900	Adiabatic	137	127	186	105	2c	100	0.5	10	72	125	150	41
1d	900	Convective	132	122	179	100	2d	100	0.5	40	67	129	138	37
							2e	180	0.05	10	71	125	151	34
							2f	100	0.05	10	71	125	150	34
							2g	180	0.05	40	64	127	138	32
							2h	100	0.05	40	63	126	137	30

2.2 Pre-heating within the cell

Eight different scenarios are considered, summarized in table 1, representing different gas velocities (u_g), gas temperature (T_g) and height of new anode above crust (h). The temperature in the anode center, T_{core}, centerpoints of top (T_{min}) and bottom (T_{bottom}) surfaces as well as the maximum temperature (T_{max}) after 210 minutes is given in the table, with sampling points and the temperature distribution for Case 2h is shown in figure 2b for reference.

3 Industrial measurements

As indicated in table 1, the two proposed concepts allow for core and surface temperatures of up to 137°C and 186°C, respectively. Simulations indicate that pre-heating

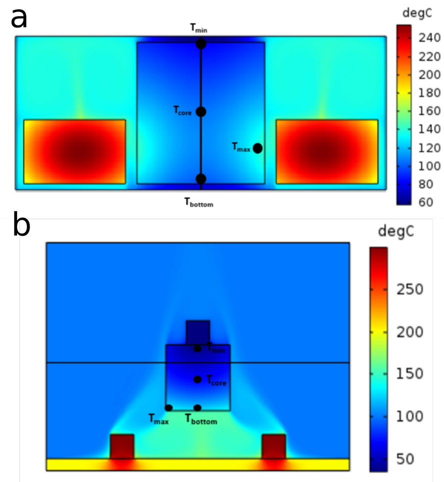

Fig. 2 Position of temperature sampling points and temperature distribution for pre-heating by butts (a) and within cell (b).

using butts appears to be more efficient than heating within the cell. Moreover, the external heating concept is simpler to realize as no modifications to the cell are required. Consequently, this concept was investigated further in an industrial setting at the Alcoa Mosjøen smelter.

The pre-heating process was performed in containers used to store butts at Alcoa Mosjøen. The anode containers were insulated in the bottom using a layer of heat resistant plates in the bottom followed by a layer of refractory bricks, as shown in figure 3a. A single new (cold) anode was placed in the centre of the insulated anode container with 4 standard K-type thermocouples, positioned along the centerline wrt. length and thickness and at approximately 1/5 intervals along the anode width, approximately 30 cm into the anode. An anode butt was placed on each side of the cold anode and temperature data was collected using a portable logging unit (AAC-2, INTAB, Sweden). During the pre-heating process, the top of the anode and the butts, as well as the side walls of the container were covered in mineral wool and insulation blankets, cf. figure 3b. Anodes were heated for 1, 2 or 4 hours and then placed in the cell as a part of the standard anode change.

All pre-heating experiments were performed during the course of a single anode change cycle, resulting in two pairs of pre-heated anodes for each heating time, as indicated in figure 4. The particular cell had continuous voltage measurements over a specific length of the anode rods, thus allowing to estimate the current pickup. It should be noted that these measurements were not precisely calibrated, as they are mostly used for an error diagnosis. A comparison to historical data from the same cell can however be used to estimate the impact of anode pre-heating on current pickup.

Fig. 3 Setup of insulation and bricks in anode container (a) and placement of butts and new anodes with insulating cover (b).

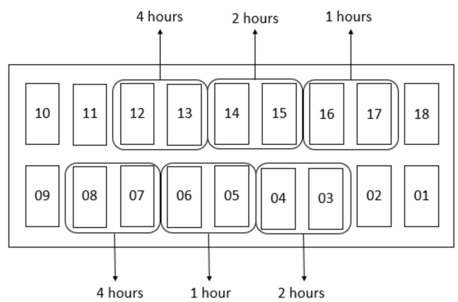

Fig. 4 Overview of anodes in cell and position of pre-heated anodes. The anodes are changed from right to left, starting with anodes 01 and 02. Anodes are replaced every 2-3 days.

3.1 Temperature and voltage evolution

Temperature data for the core and side of pre-heated anodes are shown in figure 5, where it should be noted that data on overlapping time-intervals has been merged - i.e. the curve between 0 and 1 hours includes data from pre-heating experiments aiming for 1, 2 and 4 hours duration. Simulations with adiabatic conditions correspond well to measured values, indicating that the insulation of the anode container was adequate.

The temperature distribution on the anode surface was also visualized by means of IR imaging (FLIR T440 thermal imaging camera), as shown in figure 6. As seen from the images, the slots insulate the inner portion of the anode, explaining the low surface temperature seen in the spot measurement in figure 6a.

The temperature evolution of the anode core after insertion in the cell is shown in figure 7. Due to challenges related to thermocouples becoming disconnected during anode change and anode dressing only a limited amount of data is available; the data for 1 hour pre-heating is based on four individual measurements, while only two measurements were obtained for the 2 hour case. No data was obtained for anodes pre-heated for 4 hours. Results indicate that the difference in core temperature due to

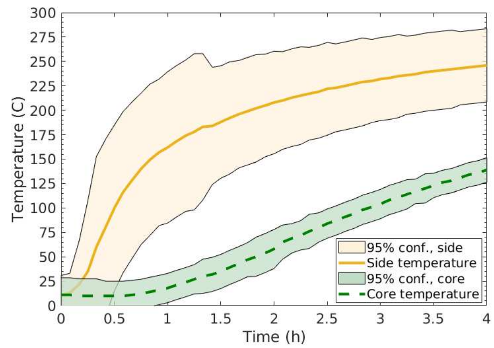

Fig. 5 Temperature evolution on side (solid orange) and core (dashed green) of anode for all pre-heating experiments with 95% confidence interval.

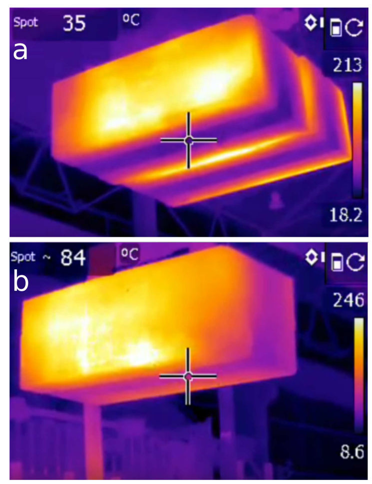

Fig. 6 IR images of anode pairs pre-heated for 1 hour (a) and single anode pre-heated for 4 hours (b) using butts.

pre-heating (cf. 5) remain for more than 15 hours, further measurements are however needed to validate this due to the large scatter in data, comparable to that reported previously by Jassim et al. [6].

A comparison between the current pickup, here represented as a voltage drop over a section of the anode hanger, for pre-heated and cold anodes is shown in figure 8. The data for cold anodes is based on historical data for the cell in question, while values for pre-heated anodes are averages based on anode pairs heated for the same time duration. As seen from the figure, pre-heated anodes from this study do not give a current pickup which is significantly different from the average for the cell in question, most likely due to variations in ACD both due to metal pad heaving and uncertainties in anode setting height - both of which are not compensated for in the current data.

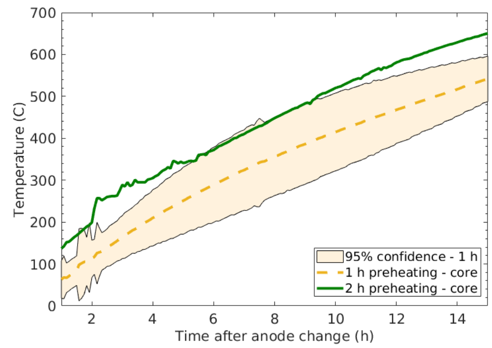

Fig. 7 Temperature evolution in anode core after insertion in cell for 1- (orange dashed line with 95% confidence interval) and 2 hour pre-heating (green solid line).

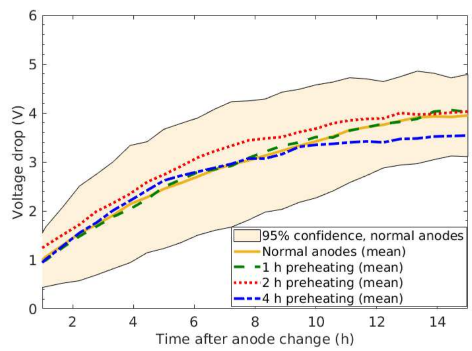

Fig. 8 95% confidence interval for voltage drop on portion of anode hanger (propotional to current density) for cold anodes (orange) and mean values for anodes pre-heated for different times.

3.2 Structure of frozen layer

An investigation of the formation of frozen bath underneath pre-heated anodes compared to cold ones was performed by removing an anode pair from a cell, where one anode had been pre-heated - thus allowing for direct comparison. Two such anode pairs were removed after 4 hours in operation, where one anode had been pre-heated for 1 hour and the second for 2 hours. Following removal, the fraction of anode bottom covered by solid bath was estimated, before the frozen bath was removed for further analysis by computer tomography (CT). The anode pair from the 2 hour heating is shown in figure 9a, along with a bath sample 9b and corresponding CT image 9c. Two representative samples were analyzed for both pre-heated and cold anodes, with main results given in table 2.

The layered structure seen in figure 9b as been observed on anodes previously [2, 3, 10], but also on rafts [11], albeit with lower porosity and smaller pore size. As observed by Poncsak et al. [10], the frozen bath is more compact close to the surface where it first freezes - i.e. the anode (upper part of the images). This region is also less porous that those further from the anode. Other than the (unsurprising) differences in anode coverage and layer thickness, the properties of the frozen bath layer do not appear to depend strongly upon pre-heating time.

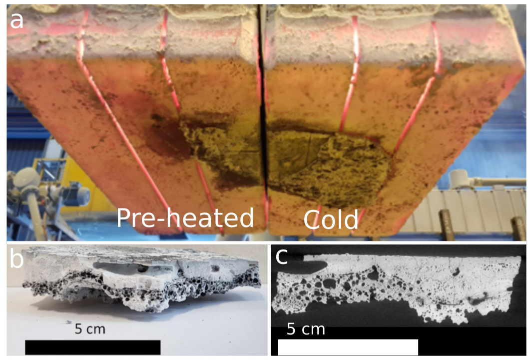

Fig. 9 Pre-heated and cold anodes after 4 hours in operation (a) with sample from cold anode (b) and CT image of the same sample (c).

Table 2 Principal results from collected bath samples.

	1 hour		2 hour	
	Pre-heated	Cold	Pre-heated	Cold
Anode coverage (%)	35	54	12	25
Layer thickness (cm)	4.1	3.7	1.4	2.0
Average pore size (mm)	0.5	0.7	0.4	0.7
Minimum pore size (mm)	0.1	0.2	0.2	0.3
Maximum pore size (mm)	5.2	4.0	2.7	6.2
Porosity (%)	11	8	6	14

4 Discussion and concluding remarks

Pre-heating of anodes reduces the heat needed for bringing the carbon ready for reaction. It can be discussed, however, if pre-heating of the feedstock leads to energy saving per se. Reducing heat losses is not trivial, and in a situation where the cell is already over-insulated in an attempt of saving energy, pre-heating may make matters worse since the cooling effect is lost.

Setting of new anodes and the subsequent period with thermal imbalance and strongly non-uniform current distribution represent the most severe disturbances in the operation of aluminium electrolysis cells. The bath and metal flow patterns as well as the shape of the metal pool will change in this period, the latter leading to some anodes having too low anode-cathode distance. Consequently, the current efficiency will be lower. Shortening of this period of disturbance will be the main benefit of pre-heating. The effect is difficult to quantify, but the 0.5-1 % improvement in current efficiency reported by Fortini et al. [5] may be realistic. 1 % increased current efficiency represents a saving of about 0.15 kWh/kg Al, which is about the same amount of energy as needed for bringing the anode from room temperature to cell temperature. Considering the average core temperature of 140° attained in the current experiments after 4 hours pre-heating, this corresponds to a (potential) energy saving of approximately 0.018 kWh/kg Al. This number could in principle be increased further by improving the design of the anode container. Furthermore, the container should be designed to house equal amounts of butts and new anodes if it is to be realized industrially. By improving the design, care should be taken to avoid air-burn. Although not relevant at the temperatures attained in the current study, this is likely to set a practical limit as to how far new anodes should be heated.

Although the current experiments do not show a dependency between pre-heating and current pick-up, this feature has already been demonstrated by Jassim et al. [6]. There is no physical reason to believe that pre-heating does not give more rapid current pick-up, although the effect in the current study apparently was obscured by random variations, e.g., in the anode setting depth or the metal heaving.

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